



REDUCED-ENGINE TAXI: A COST-SAVINGS EXPLORATION

GRADUATE RESEARCH PAPER

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REDUCED-ENGINE TAXI: A COST-SAVINGS EXPLORATION

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Abstract

Reduced-engine taxi procedures are a tactical issue with operational and strategic-level impacts. In the execution of Rapid Global Mobility, the MAF's reliance on energy makes it particularly vulnerable to shifts and adaptations in the energy market. This dependence underpins the criticality of research exploiting margins for energy savings and optimization. This research explores the viability of C-17 reduced-engine taxi procedures from a cost-savings and capability perspective.

This study models expected engine fuel flow based on number of operational engines, aircraft gross weight, and average aircraft groundspeed. Using this model, the research executes a cost-savings simulation estimating the expected annual savings produced by the proposed taxi methodology. Finally, this research proposes an optimal taxi policy model which prescribes either a two-engine or four-engine taxi methodology based on aircraft gross weight and minimization of excessive jet blast.

The results indicate that significant fuel and costs savings are available via the employment of reduced-engine taxi procedures. On an annual basis, the MAF has the capacity to save approximately 1,178,590 gallons of jet fuel (\$2,663,613 in fuel costs) without adding significant risk to operations. The two-engine taxi methodology has the ability to generate capable taxi thrust for a maximum gross weight C-17. This research recommends coordination with Boeing to rework checklists and flight manuals, installation of a fleet-wide training program, and evaluation of future aircraft recapitalization requirements intended to exploit and maximize savings during aircraft surface operations.

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Table of Contents

	Page
Acknowledgments.....	iv
List of Figures	vii
List of Tables	viii
List of Equations.....	ix
I. Introduction	1
Background and Motivation.....	1
Problem and Purpose Statement.....	3
Research Objectives/Questions/Hypotheses	4
Research Focus/Scope.....	5
Assumptions/Limitations	6
Methodology	8
Theory	9
Implications.....	10
II. Literature Review.....	11
Chapter Overview	11
Resource Dependence Theory.....	11
Reduced-Engine Taxi.....	13
Added Benefits of Reduced-Engine Taxi	15
Reduced-Engine Taxi Limitations	16
Commercial Airline Applications	17
C-17 Operations and Regulations	18
Summary	19
III. Methodology	20
Chapter Overview	20
Data Sources	21
Data Description.....	22
Mathematical Proof of Theoretical Benefits.....	24
Data Analysis and Synthesis	26
Fuel-Savings Comparison Model.....	27
Cost-Savings Simulation.....	30
Optimal Taxi Policy Model.....	31
Summary	35

IV. Analysis and Results.....	37
Chapter Overview	37
Results of Fuel-Savings Comparison Model	37
Results of Cost-Savings Simulation.....	41
Results of Optimal Taxi Policy Model	45
Summary	50
V. Conclusions and Recommendations	51
Chapter Overview	51
Conclusions of Research	51
Significance of Research.....	53
Recommendations for Action	54
Recommendations for Future Research	56
Summary	57
Bibliography	58
Appendix: Quad Chart	61

List of Figures

	Page
Figure 1. Four-Engine and Two-Engine (Predicted) Fuel Flow per Operational Engine Comparison.....	38
Figure 2. Four-Engine and Two-Engine (Predicted) Total Fuel Flow Comparison	39
Figure 3. Cumulative Savings (\$) vs. Number of Sorties	44
Figure 4. Comparison of Model vs. Actual Engine Pressure Ratios per Data Point	46
Figure 5. Average Engine Pressure Ratio vs. Aircraft Gross Weight.....	47

List of Tables

	Page
Table 1. Model Outputs for Parameter Estimates of Average Engine Fuel Flow per Operational Engine	28
Table 2. Refined Model Outputs for Parameter Estimates of Average Engine Fuel Flow per Operational Engine	29
Table 3. Model Outputs for Parameter Estimates of Average Engine Pressure Ratio per Operational Engine	33
Table 4. Refined Model Outputs for Parameter Estimates of Average Engine Pressure Ratio.....	34
Table 5. Four-Engine versus Two-Engine Taxi Savings Comparison	40
Table 6. Operational Risk Penalties of Reduced-Engine Taxi Procedures.....	42
Table 7. Total Fuel and Cost Savings Produced by Comparison of Four-Engine and Reduced-Engine Taxi Procedures per Number of C-17 Sorties	43
Table 8. Modeled Two-Engine Average Engine Pressure Ratio Requirements per Aircraft Gross Weight	48
Table 9. Maximum Engine Pressure Ratio Observed for Each Engine per Taxi-Out Data Samples.....	49

List of Equations

	Page
Equation (1)	25
Equation (2)	25
Equation (3)	27
Equation (4)	28
Equation (5)	32
Equation (6)	34

REDUCED-ENGINE TAXI: A COST-SAVINGS EXPLORATION

I. Introduction

“The fiscal choices we face are difficult ones, but there should be no doubt – here in the United States or around the world – we will keep our Armed Forces the best-trained, best-led, best-equipped fighting force in history. And in a changing world that demands our leadership, the United States of America will remain the greatest force for freedom and security that the world has ever known.”

-President Barack Obama, 3 January 2012

Background and Motivation

Energy is critical to the security and welfare of our nation. As the largest user of petroleum in the world (Schwartz, 2012), the Department of Defense (DoD) must explore methods to reduce its overreliance on energy resources. The DoD’s global presence creates a lengthy logistical tail requiring sustained, worldwide mobility of people and resources. Dependence on the shared logistical necessities required to support national priorities and global operations places the nation at financial, operational, and strategic risk. In an environment of limited and diminishing resources, the accessibility of energy will directly impact our nation’s capability to perform its operational mission and provide for the common defense.

In his “Sustaining U.S. Global Leadership: Priorities for the 21st Century Defense” directive, President Barack Obama mandated reductions in defense spending (DoD, 2016). To comply with this directive, Secretary of Defense Robert Gates directed the military services to reduce their monetary footprints. One of Secretary Gates’

primary emphasis items was to reduce fuel and energy consumption within the United States Air Force (USAF)'s Air Mobility Command (AMC). In this mandate, Secretary Gates required the USAF to develop a plan to reduce AMC's fuel usage by \$700 million dollars from fiscal year 2012 to fiscal year 2016 (Comptroller, 2012).

To comply with this aggressive demand, the USAF developed distinct energy priorities – Improve Resiliency, Reduce Demand, Assure Supply, and Foster an Energy Aware Culture (Donley, 2013). AMC translated this directive into a comprehensive evaluation of its mobility mission. Specifically, the program reviewed aircraft maintenance and modernization, aircraft loading procedures, flight plan routing, flight scheduling, and operational mission execution (Joyner, 2011). To further investigate capacities for potential fuel conservation, the USAF reviewed and analyzed the commercial aviation industry, which boasted a five-percent fuel reduction in fuel consumption from 2000 through 2006 while increasing their passenger movement by 12 percent and their cargo movement by 22 percent (Joyner, 2011). Today, researchers continue to evaluate margins for operational fuel efficiencies within the aviation community.

The purpose of this research is to evaluate the potential fuel and cost savings underpinned by implementation of a reduced-engine taxi maneuver during sustained periods of taxi prior to initial takeoff. This research will offer an optimal taxi policy prescribing either a four-engine or two-engine taxi strategy based on aircraft gross weight; symmetry is assumed to be important in maintaining control of the aircraft, so a three-engine reduced-taxi model will not be considered. Current Mobility Air Force (MAF) culture encourages mobility aircraft to start all engines prior to taxiing from their

parking spots. This practice yields an optimization misbalance between thrust required to taxi and fuel expended during the taxi maneuver.

The commercial airlines often conserve fuel by taxiing on only the number of engines required to produce capable taxi thrust. This comparatively better business practice used in the commercial airline industry should prove to drive efficiencies in the USAF. As the USAF continues to evaluate margins for monetary and energy savings, AMC must consider operational best practices that yield efficiencies without impacting effectiveness. This study evaluates the potential fuel and energy savings produced by implementation of reduced-engine taxi procedures during C-17 operations. When appropriate conditions exist, this taxiing strategy has the capacity to broaden the margins for fuel-savings initiatives. This research will produce recommendations that result in an increasingly capable and more efficient fighting force ready to deliver Rapid Global Mobility around the globe.

Problem and Purpose Statement

Air Force fuel savings are of utmost importance as energy sources decrease and prices continue to increase. Because of the magnitude of costs associated with operating mobility aircraft in a fiscally-constrained environment, AMC must streamline its practices, optimize fuel usage, and decrease costs. The purpose of this study is to explore the potential fuel savings and subsequent fiscal advantages gained by the C-17 community adopting a practice of taxiing on a reduced number of engines prior to initial takeoff. The efficiency of this practice will be compared to the technical and operational risks associated with executing this maneuver. In addition, this research will recommend

an optimal taxi policy model which will prescribe the use of either a four-engine or reduced-engine taxi methodology based on optimizing capable taxi thrust while minimizing excessive jet blast.

Research Objectives/Questions/Hypotheses

The aim of this research is to determine if it is beneficial for AMC to adopt a procedure that provides C-17 pilots with the option of delaying engine start during sustained periods of taxi prior to initial takeoff. To achieve this objective, this research will identify the prospective fuel savings of the reduced-engine taxi maneuver associated with standard taxi operations at four C-17 main operating bases (i.e., Charleston Air Force Base, South Carolina; Ramstein Air Base, Germany; Travis Air Force Base, California; and Joint Base Pearl Harbor-Hickam, Hawaii). This research will analyze the fuel efficiencies against the impacts of possible maintenance issues following initiation of the taxi maneuver. Additionally, this research will create an optimal taxi policy model to recommend guidelines for when crew members should employ the reduced-engine taxiing strategy based on aircraft gross weight.

To fulfill the aforementioned research objectives, this thesis will investigate the following specific research questions:

1. On an annual basis, how much fuel can the MAF save by implementing reduced-engine taxi procedures?
2. How do potential fuel savings from reduced-engine taxi procedures compare to the risks of engine-start malfunctions and subsequent back taxi maneuvers?

3. How does aircraft gross weight impact the reduced-engine taxi procedure's average thrust requirements to produce capable taxi thrust during sustained periods of taxi?

Synthesizing the expected results from these research questions, C-17 reduced-engine taxi procedures are hypothesized to have great potential to produce significant fuel and cost savings. Safety and maintenance reliability concerns will be negligible. The commercial aviation industry employs reduced-engine taxi procedures as an effective business practice to mitigate their enterprise's fuel costs. AMC should consider the practical applications, risks, and opportunities associated with reduced-engine taxi procedures and afford pilots the opportunity to exercise this practice as a valid taxi technique. Reduced-engine taxi has the potential to save millions of dollars in annual fuel costs when employed as an accepted and practiced procedure in daily operations.

Research Focus/Scope

Reduced-engine taxi procedures are applicable to the entire MAF fleet with airframe-dependent operational caveats that demand specialized investigation and research. However, the scope of this project is bound specifically to the impacts of reduced-engine taxi procedures on the C-17 community. This research builds a cost-savings simulation and an optimal taxi policy model by incorporating taxi-out and taxi-in data from four C-17 main operating bases (i.e., Charleston Air Force Base, South Carolina; Ramstein Air Base, Germany; Travis Air Force Base, California; and Joint

Base Pearl Harbor-Hickam, Hawaii). This research will not incorporate data from any Foreign Military Sales aircraft.

Delaying engine start (albeit by minutes) can lessen the fatigue on various aircraft systems. Reduced-engine taxi procedures can decrease engine wear and tear over an engine's lifespan. Besides annotating the innate benefits associated with less demand on the propulsion system, this research will not evaluate the benefits of reduced-engine taxi procedures on extending engine life. Because these procedures allow for optimization of taxi thrust production, this taxi methodology caters to a decrease of aircraft braking. This research will not explore the benefits of this procedure on the aircraft braking system.

Lastly, this research will account for employment of reduced-engine taxi procedures during training and global mission execution at only four specific C-17 main operating bases. This research will not address or evaluate the tactical implications of starting less than the full complement of an aircraft's engines while taxiing on a combat airfield. For the purposes of this research, employment of this procedure will not be dependent on a pilot's qualification level. The least experienced crew complement (i.e., an aircraft commander and new first pilot) will be able to safely employ reduced-engine taxi procedures. The intent of incorporating the C-17's entire mission set will allow the research to account for disparities and taxi adjustments due to varying operational factors including aircraft gross weight and outside air temperature.

Assumptions/Limitations

This research uses several assumptions. To begin, engine fatigue and age will negligibly impact overall fuel flow rate. All calculations will assume that C-17 engines

perform at levels of operation commensurate to the analyzed data samples. The research will not account for unique engine characteristics of specific aircraft (i.e., low-margin engines or abnormal fuel flows). Furthermore, for each data sample, calculations will assume that all engines on a respective aircraft perform equally in terms of thrust produced and fuel consumed during the taxi maneuver. Pilots have the ability to employ asymmetrical thrust during the taxi maneuver to tighten their turning radius. However, for the purposes of this investigation, results will be predicated on employment of symmetrical thrust practices.

Taxi time is a primary determinant in fuel consumption. As such, taxi operations are assumed to have occurred along the most efficient route of travel. Human error, if present, during aircraft operation or the data collection process is negligible. To calculate and compare fuel consumption during a taxi maneuver, this research will assume that fuel savings are only available during the course of the taxi maneuver. Significant fuel consumption savings and costs will not be evaluated prior to initiation of the taxi maneuver or during delays associated with engine warm-up requirements.

Due to varying tactical employment and weather considerations, this research will assume that reduced-engine taxi procedures are only applicable during 50 percent of C-17 sorties. The intent of this procedure is to offer pilots a viable taxiing strategy for employment at their individual discretion; this study will assume that pilots employ this technique on half of their executed sorties. Additionally, to evaluate anticipated utilization of the proposed procedure, this study assumes that historical averages of aircraft employment and performance will be predictive of future MAF operations. This

assumption will allow the research to predict future cost-savings of C-17 reduced-engine taxi procedures.

This research also has limitations. First, the amount of historical Military Flight Operations Quality Assurance (MFOQA) data available for the C-17 is extensive. There are 2,099 data channels collecting data per data file. Due to limited time available for data analysis, this research will analyze 35 data files comprised of initial C-17 departures and full-stop arrivals from the aforementioned four main operating bases. Second, MFOQA data does not record when less than three engines are operating on the aircraft. Therefore, two-engine taxiing data was not available for analysis. This research extrapolated the four-engine and three-engine taxiing data to yield estimates for two-engine operations.

Methodology

The Headquarters AMC Analysis, Assessments, and Lessons Learned Directorate (AMC/A9) in coordination with the Operations Directorate (AMC/A3) provided the MFOQA data required to construct the models and simulation. To estimate the potential fuel savings that exist from reduced-engine taxi procedures, this research developed two linear least-square regression models and one simulation using Microsoft Excel. The fuel-savings comparison model will estimate the average fuel flow required for each operational engine during a nominal taxi maneuver. Using engine data from thirty-five operational missions at four unique C-17 main operating bases, the model calculates a representative sample of the potential fuel savings from the reduced-engine taxi strategy across the comprehensive C-17 mission set.

Additionally, the research developed a simulation that approximated fuel penalties caused by potential engine-start malfunctions during delayed engine-start procedures. Using a Monte Carlo simulation and executing 52,000 simulations, the study calculated the net annual impacts of the fuel and cost savings compared to the risks of engine-start malfunctions during the taxi maneuver. The results of this simulation determined if the energy and fiscal savings of the C-17 reduced-engine taxi maneuver are sufficient to compensate for the costs of potential operational risks.

Lastly, the optimal taxi policy will prescribe either a four-engine or two-engine taxi strategy based on aircraft gross weight; symmetry is assumed to be important in maintaining control of the aircraft, so a three-engine reduced-taxi model was not considered. Per the results of the literature review, excessive jet blast was determined as the primary operational concern when considering a reduced-engine taxi methodology. The results of the optimal taxi policy model will recommend guidelines for when pilots should employ the reduced-engine taxi procedure as influenced by engine pressure ratio (the total pressure ratio across a jet engine) and aircraft gross weight.

Theory

The resource dependence theory explains behavior driving fuel-savings explorations and initiatives. This theory suggests that external resources upon which the firm is dependent impact an organization's behavior. The procurement of external resources is an important aspect of a company's strategic and tactical management. Over the past decade, financial limitations and energy constraints have forced AMC to fundamentally alter its energy awareness and operating practices. A RAND investigation

stated that “over the next 50 years, fuel reserves [will] continue to be depleted and as supplies diminish, prices will escalate and availability will become less certain both home and abroad” (Gebman et al., 1976). Given the anticipated fiscal and energy constraints facing the DoD, the resource dependence theory suggests that AMC may alter its behavior to maximize its resources and operational effectiveness. AMC’s current and sustained fuel-savings studies and initiatives clearly validate this theory’s application to this research.

Implications

The results of this research could save millions of dollars for the DoD, the USAF, and AMC. Evaluating and refining C-17 taxi procedures will directly impact MAF fuel efficiency. It provides potential to alter C-17 major weapon system employment by implementing and training aircrew to a new “reduced-engine taxi” checklist option prior to initial departure. This taxi strategy will fundamentally alter aircrew training and facilitate a culture shift in the delegation of aircraft duties during the taxi maneuver. In a global economy bound by limited resources, the USAF will gain a competitive advantage by efficiently leveraging its logistical resources. Furthermore, the factors and efficiencies identified in this research can offer insight into the future of aircraft recapitalization requirements.

II. Literature Review

Chapter Overview

Fuel efficiency has been an USAF priority since 1944 when Charles A. Lindbergh taught Army aviators how to maximize their fuel to extend their range and “carry more ordnance, provide longer range escorts to bombers, and return with more fuel than planned” (Brown, 2011). This chapter will present and review literature that experts have presented with regards to the fuel-savings potential of reduced-engine taxi procedures. Specifically, this chapter will address the resource dependence theory, reduced-engine taxi procedures, added benefits of reduced-engine taxi procedures, reduced-engine taxi limitations, commercial airline applications, and C-17 operations and regulations. This literature review addresses both the inherent benefits and associated concerns of implementing C-17 reduced-engine taxi procedures.

Resource Dependence Theory

The resource dependence theory explains the governing behavior leading to fuel savings concerns and AMC’s exploration of “fuel-efficiency initiatives.” Brigadier General Mark Brown (2011) observed that when leaders face resource constraints, they must “make trade-off decisions and live within those constraints while minimizing adverse effects on the mission.” Because Secretary Gates required the USAF to reduce mobility aircraft fuel usage by \$700 million dollars from fiscal year 2012 to fiscal year 2016 (Comptroller, 2012), senior leaders were faced with the unique challenge of balancing risk and responsibly reducing fuel consumption while sustaining mission

effectiveness. Today, fiscal constraints and limitations continue to alter behavior and underpin the necessity of optimizing scarce resources.

The resource dependence theory recognizes the influence of external factors on organizational behavior (Hillman et al., 2009). According to this theory, organizations will strive to minimize uncertainty and dependence and maximize [their] autonomy (Davis and Cobb, 2009). This theory informs the research design by acknowledging that AMC should adapt its organizational behavior due to limitations of critical resources. The central proposition of resource dependence theory stipulates that “organizations (or organizational sub-units) controlling resources that other actors need have power over these actors” (Nienhüser, 2008). This theory suggests that the United States government will retain power over the DoD’s behaviors due to the inextricable linkage between the organizations. Given restricted maneuverability to acquire additional resources, AMC should be expected to alter its behavior by exploring fuel-efficiency initiatives and solutions, thereby reducing its dependence on the limiting resource.

This theory illuminates why reducing fuel consumption is a priority for the USAF. A dependence on external energy resources (coupled with monetary limitations) is driving AMC’s behavior in terms of fuel conservation. Heavy resource dependence threatens organizational maturation and effectiveness. Senior leaders are aware of multiple solutions that decrease fuel consumption, and they should conduct a cost-risk analysis to determine acceptable levels of assumed risk for implementation. Predictions from this theory suggest that AMC should explore these solutions, adjust its behaviors accordingly, and optimize its resources to sustain operational readiness.

Literature shows that engineers are well-aware of alternatives that provide opportunities for the USAF to yield better fuel savings and fuel efficiencies. The primary obstacle is to “[determine] which initiatives to implement, and in what order, to maximize efficiency” (Brown, 2011). Tactical-level operations such as flight planning, optimizing fuel loads, and reconfiguring cargo configurations have produced immediate and positive results (Brown, 2011). Literature reveals capacity for further fuel savings via more efficient ground and flight operations. Mouton et al. (2015) highlights available fuel efficiencies and operational gains via reduced-engine taxiing procedures. This taxi strategy offers a solution for more efficient operations without adding significant risk to mission execution (Marias et al., 2012).

Reduced-Engine Taxi

Marias et al. (2012) observed that nominal aircraft surface operations account for a relatively small proportion of total system fuel burn, but there are opportunities for meaningful environmental impacts and fuel savings due to surface congestion and delays. Ithnan et al. (2013) stated that over time the growth rate of the total taxiing time in the airline industry has been larger than the airborne time growth rate and the total mission time growth rate. This increased taxi time directly correlates to an increase in fuel expenditures during surface operations and highlights the importance of optimizing operations during ground movements (Ithnan et al., 2013). Page (2012) suggests reduced-engine taxi operations as a viable solution to help minimize fuel burn and offset the aforementioned ground operation costs.

Reduced-engine taxi is well-documented in literature as an effective fuel-savings initiative with minimal risk to operations. Research has shown that this taxiing strategy can “[reduce] ground fuel burn by up to 40 percent” (Page, 2009). Heseltine (2007) cited this technique as an opportunity for KC-135s to review their operations and generate significant cost savings. The reduced-engine taxi methodology is a valid aircraft ground movement technique that is characterized by maneuvering an aircraft during the taxi-phase of operation with less than an aircraft’s full-complement of engines (Marias et al., 2012). During the taxi maneuver, aircraft do not require all engines for taxiing because the idle thrust produced by a subset of the engine is sufficient for ground movement (Mouton et al., 2015). When pilots employ this taxi strategy and use only the number of engines required to execute the taxi maneuver, they reduce their respective aircraft’s overall fuel consumption during surface operations. Research shows this strategy has the potential for system-wide impact and easy implementation (Marias et al., 2012).

In a comprehensive study of sixteen different fuel savings initiatives, Mouton et al. (2015) established that reduced-engine taxi procedures can provide the USAF with the greatest cost-effectiveness from a fuel-savings perspective. Reduced-engine taxi procedures require no extra physical investments on the aircraft or airfield (Ithnan et al., 2013). By simply taxiing on only the engines required to perform the taxi maneuver, pilots can reduce their aircraft’s fuel burn without additional cost (Mouton et al., 2015). With the required infrastructure already in place, reduced-engine taxi is applicable to all aircraft, and pilots can quickly and immediately implement the strategy in their daily operations (Ithnan et al., 2013). As Martin Alder, the former Flight Safety Group chief of

the British Airline Pilots' Association, stated, "if pilots are given guidance for when [reduced-engine taxi] is appropriate, and if it's left to their discretion, then it can be done relatively easily" (Page, 2009).

Added Benefits of Reduced-Engine Taxi

In addition to fuel savings, reduced-engine taxi procedures provide added benefits to the environment and an aircraft's longevity. Marias et al. (2012) observed that there is increasing pressure on the aviation community to mitigate the environmental impacts of aviation. Nikoleris et al. (2011) determined that taxi operations are often the largest source of harmful emissions during a standard landing take-off cycle around airports. Jordao et al. (2011) determined that most airlines attempt to minimize their carbon dioxide emissions by optimizing their fuel consumption. By optimizing the C-17's surface operations via reduced-engine taxi procedures, the USAF can lessen their harmful emissions and positively contribute to environmental sustainment.

Reduced-engine taxi procedures have the potential to yield maintenance savings and contribute to aircraft longevity. Hospodka (2011) identified less brake wear-out and improved engine life as two primary benefits of optimizing engine operation. Mouton et al. (2015) noted that at low aircraft gross weights, the idle thrust of all engines far exceeds that required to taxi the aircraft. As a result, crews may be required to apply continued braking force during movement. By employing a reduced-engine taxi strategy, pilots can optimize their capable taxi thrust and eliminate excessive brake applications. This taxi strategy also decreases working time of the aircraft's engines. Maintenance costs and inspections are tied to engine operating hours (Hospodka, 2011).

Reduced-engine taxi procedures encourage optimization of engine employment and a reduction of unnecessary engine operations. Given the nature of this methodology, Hospodka (2011) predicted significant savings of maintenance costs and engine working time costs. Literature shows that the operational savings of reduced-engine taxi extend beyond fuel-efficiency initiatives and make it an enticing prospect for standard ground operations.

Reduced-Engine Taxi Limitations

Literature proves that reduced-engine taxi procedures are a cost-effective method for generating fuel savings. However, limitations do exist. Marias et al. (2012) observed that there can be reluctance from pilots to use reduced-engine taxi procedures for operational reasons (Marias et al., 2012). A pilot's reluctance to employ this taxi technique stems from increased risk due to potential for engine-start malfunctions after departure from the gate (Marias et al., 2012). Additionally, the reduced-engine taxi procedure requires pilots to accept risk inherent to starting engines while concurrently performing the taxi maneuver. Specifically, pilots must maintain situational awareness of their external environment while starting engines and simultaneously performing the taxi maneuver. Other factors include the potential of ingesting foreign object debris, generating jet blast and damaging other aircraft on the taxiways, and losing situational awareness due to multi-tasking during the taxi maneuver.

Hao et al. (2016) acknowledged that pilots cannot always execute the reduced-engine taxi procedure because the airfield is sensitive to numerous factors including jet blast from larger aircraft types. Before employing the reduced-engine taxi

procedure, pilots must consider the aircraft's gross weight, engine thrust, and the impact of higher thrust settings to the external environment (Hao et al., 2016). Ithnan et al. (2013) noted that the reduced-engine taxi maneuver can create jet blast that could lead to safety issues such as hazardous situations for nearby work in progress. Despite reluctance and added risk, reduced-engine taxi procedures have been successfully implemented throughout the airline industry when pilots are provided with specific employment considerations (Marias et al., 2012).

Aircraft operational limits, taxi routes, and environmental conditions also yield limitations to employment of this procedure. Ithnan et al. (2013) observed that depending on the engine manufacturer, the aircraft engine still needs to be warmed-up after being turned-on, or cooled-down before being switched-off which takes around two to five minutes. Therefore, this strategy will only be effective if the taxiing time is longer than the engine's warm-up or cool-down time (Ithnan et al., 2013). Mouton et al. (2015) stated that taxiing on fewer engines may require longer launch times to start all engines and allow adequate engine warm-up at the end of the runway. Airbus also does not recommend this procedure for uphill slopes or slippery surfaces, when deicing operations are required, and when there are sharp and tight taxiway turns (Ithnan et al., 2013). Pilots must consider these limitations when determining the appropriate taxi methodology for ground movement.

Commercial Airline Applications

The commercial airline industry has widely implemented single-engine taxi procedures throughout its enterprise. The single-engine taxi is a variant of the

reduced-engine taxi procedure; it is pertinent to the commercial airline industry because most aircraft within the commercial airline fleet contain only two engines. A report from the International Civil Aviation Organization (2012) stated that single-engine taxi procedures should be used whenever possible to reduce emissions and save fuel resources. Most airline companies recommend using the single-engine taxi procedure during taxi when safe and operationally feasible (Hao et al., 2016). Jet Blue, Alaska Airlines, and American Airlines each realized savings by providing their pilots with the opportunity to execute single-engine taxi procedure during ground operations.

Mouton et al. (2015) discovered that JetBlue's E190 fleet has employed a single-engine taxi technique since the beginning of 2005, and this same technique is standard operating procedure for A320 aircraft (unless weather or airport layout cause it to be infeasible). Throughout its enterprise, Jet Blue implements this procedure on over half of its flights (Mouton et al., 2015). Similarly, Alaska Airlines employs this taxi strategy throughout its system, and their 2009 figures show a resultant savings of 260,000 gallons of fuel. American Airlines claimed that the procedure saved more than two million gallons of jet fuel annually (Hao et al., 2016). When applied across their fleet, American Airlines recognized a 30-percent fuel reduction during the taxi maneuver and \$4M in annual savings (Heseltine, 2007). The commercial airline industry serves as a successful case study for employment of the reduced-engine taxi procedure.

C-17 Operations and Regulations

Air Force Instructions for C-17 operations dictate that pilots should consider engine-out taxi procedures when permitted by the flight manual (Department of the Air

Force, 2015). However, the standard C-17 consolidated checklist only incorporates a procedure for engine-out taxi during the taxi portion of flight following the final landing and immediately prior to mission termination. For standard operations, the USAF has not published employment guidelines and procedures for reduced-engine taxi procedures prior to the mission's initial takeoff. In interviews with MAF crews, Mouton et al. (2015) determined that crews take advantage of the opportunity to execute engine-out taxi procedures following the final landing, but it is not universal. Air Force Instructions cater to the implementation of the reduced-engine taxi procedures. USAF leaders must investigate updates to the aircraft flight manuals and provide the crew force with alternative procedures and instructions allowing them to maximize the opportunities of reduced-engine taxi procedures.

Summary

Reduced-engine taxi is well-documented in literature as an effective fuel-savings initiative with minimal risk to operations. This chapter discussed the benefits and limitations of implementing the reduced-engine taxi procedure across the C-17 enterprise. It provided a basic understanding of how fuel-savings initiatives correlate to the resource dependence theory. Finally, this chapter discussed the added benefits of reduced-engine taxi procedures, the commercial airline applications, and the C-17 operations and regulations guiding this procedure.

III. Methodology

Chapter Overview

This chapter outlines the methodology used to assess the impacts of C-17 reduced-engine taxi procedures on USAF fuel consumption. Specifically, this methodology is used to develop a policy model for C-17 reduced-engine taxi employment and answer three research questions. First, how much fuel can the MAF save by implementing reduced-engine taxi procedures? Second, how do potential fuel savings from reduced-engine taxi procedures compare to the risks of engine-start malfunctions and subsequent back taxi maneuvers? Third, how does aircraft gross weight impact the reduced-engine taxi procedure's average thrust requirements to produce capable taxi thrust during sustained periods of taxi?

To answer these questions, this research used a model and simulation typology. This typology allowed for the derivation of two models (a fuel-savings comparison model and an optimal taxi policy model) using statistical least-squares regression from real-world data. Based on the derived fuel-savings comparison model, potential fuel savings for the reduced-engine taxi procedure were estimated via development and execution of a cost-savings simulation. This simulation considered and applied a fuel consumption penalty for operational risk factors due to engine-start malfunctions. The optimal taxi policy model prescribed the use of either a four-engine or reduced-engine taxi methodology. The focus of this policy was to mitigate excessive jet blast risks and recommend ideal employment options to pilots based on aircraft gross weight.

This research utilized pre-existing MFOQA data and maintenance data as the primary sources of data. These data sources provided aircraft performance characteristics

and allowed for the characterization of the average fuel flow per operational engine required to execute the reduced-engine taxi maneuver (fuel-savings comparison model). It also provided insights on potential monetary savings of reduced-engine taxi procedures (cost-comparison simulation) and allowed for the development of a policy model outlining appropriate employment dependent on optimization of jet blast as defined by average engine pressure ratio (optimal taxi policy model).

Data Sources

To measure an aircraft's taxi characteristics and associated fuel consumption, historical, pre-existing MFOQA data was collected from Headquarters AMC. Data samples were harvested from C-17 sorties originating at four unique main operating bases and translated into a Microsoft Excel spreadsheet for analysis. MFOQA data is similar to flight recorder data and allows AMC's Director of Operations to perform quality assurance assessments on pilots' flying behaviors. This data hub collects aircraft performance characteristics and parameters during various phases of aircraft operations. The data are used to analyze pilot flying behavior and create policies that result in safer and more efficient flying operations. For this research, the data allowed for the evaluation of performance characteristics during the taxi phase of operation, analysis of engine consumption characteristics given various four-engine and reduced-engine taxi methodologies, investigation of the impacts of aircraft taxi variables on engine pressure ratios, and identification of margins for fuel efficiencies during surface operations.

Maintenance data from the Air Force GO81 (Aircraft Mobility Data Systems) database maintained at the Headquarters AMC Logistics Directorate (AMC/A4) are also

used in this research. This data was used to determine the average percentage of C-17 engine-start malfunctions experienced per year. A detailed evaluation of the average percentage of engine-start malfunctions is critical to determining whether or not the operational risks of reduced-engine taxiing procedures outweigh the potential fuel savings. This information was incorporated in the cost-savings simulation and allowed for evaluation of the entire concept of C-17 ground operations. The experimental design incorporating this data resulted in approximated monetary savings resulting from employment of the reduced-engine taxiing strategy.

Lastly, pre-existing, historical data was used to determine the average number of C-17 sorties flown per year. This data was gleaned from a database maintained by the Headquarters AMC Analyses, Assessments, and Lessons Learned Directorate (AMC/A9). This data was used in the cost-savings simulation and provided an estimate of annual cost savings. The simulation approximated annual fuel and cost savings, assuming future operation tempos remained consistent with historical averages.

Data Description

The Headquarters AMC Analyses, Assessments, and Lessons Learned Directorate (AMC/A9) in coordination with the Operations Directorate (AMC/A3) provided 35 taxi data samples from four C-17 main operating bases (i.e., Charleston Air Force Base, South Carolina; Ramstein Air Base, Germany; Travis Air Force Base, California; and Joint Base Pearl Harbor-Hickam, Hawaii). The extracted taxi data provided two distinct taxi types (outgoing and incoming taxi patterns) from aircraft taxiing with four and three operational engines. This data was filtered in Microsoft Excel according to standardized

taxi-in and taxi-out definitions. The MFOQA data were collected at 0.25-second intervals, capturing the following variables: fuel flows for engines one through four, engine pressure ratios for engines one through four, outside air temperature, aircraft gross weight, taxi distance, taxi time, and aircraft ground speed. The dataset also included a “point of interest” variable defining specific points of operation based on aircraft configuration and location and a “weight on wheels” variable yielding either a “TRUE” or “FALSE” output dependent on if the aircraft was on the ground or airborne, respectively.

The taxi-in variable was derived from a C-17 operating limitation, which stipulates that taxi operations must occur at groundspeeds below 40 knots. For this study, taxi-in was defined as the first aircraft movement occurring at a groundspeed below 40 knots immediately following landing roll-out. The taxi-in phase of operation was terminated upon arrival into parking as defined by a sustained groundspeed of zero knots at the conclusion of the data set. Taxi-out was defined as aircraft surface movement starting with the initial movement from the parking position and terminating upon entry to the runway. Runway entry was determined using the data's "point of interest" variable. For both definitions (taxi-in and taxi-out), intermittent stops along the route of taxi were included as portions of the comprehensive taxi maneuver.

The Headquarters AMC Logistics Directorate (AMC/A4) maintains the Air Force GO81 (Aircraft Mobility Data Systems) database which tracks the health and maintenance of all C-17 aircraft in the USAF inventory. This data tracks C-17 performance metrics, aircraft employment, and maintenance trends. AMC/A4 provided query results outlining all engine malfunctions for a one-year period. The number of

engine-start malfunctions was extracted from this data and compared (using the methodology described below) to the number of engine starts accomplished across the fleet per year. This trend data revealed the average number of C-17 engine-start malfunctions experienced per year across the fleet. This data allowed for the construction of a cost-savings simulation, employment of an operational penalty of taxi costs when pilots experience engine-start malfunctions after initiation of the taxi maneuver, and calculation of an annual monetary fuel-savings approximation.

The Headquarters AMC Analyses, Assessments, and Lessons Learned Directorate (AMC/A9) maintains a database showcasing the number of sorties flown per year for each aircraft in the MAF fleet. AMC/A9 provided a single constant reflecting C-17 employment in terms of number of sorties for fiscal year 2016. This data allowed for the determination of the number of simulations required to calculate an approximation for the annual monetary savings available via employment of the reduced-engine taxi strategy.

Mathematical Proof of Theoretical Benefits

Jet engines are designed for efficient power generation at high speeds and high altitudes, but they are significantly less effective during surface-level operation (Jensen and Yutko, 2014). In an interview with Boeing, McCollum (2017) demonstrated these aircraft engine efficiency characteristics by constructing a mathematical proof. This model proves it is more efficient to employ a reduced-engine taxi strategy (i.e., two-engine taxi) instead of a four-engine taxi strategy during surface operation. The reduced-engine taxi procedures allow pilots to optimize their thrust requirements to generate applicable taxi speed. If additional power is required, pilots can increase their

thrust settings, which allows the engines to operate closer to their efficient power generation zones.

To understand engine efficiency characteristics, four variables are required: aircraft gross weight, the thrust required to perform the taxi maneuver, the specific fuel consumption, and the overall engine fuel flow required to generate thrust to execute the taxi maneuver (McCollum, 2017). McCollum (2017) estimated the thrust required to taxi a C-17 aircraft by multiplying the aircraft's gross weight (GW) by the rolling coefficient of friction (μ_r). For this specific model, the rolling coefficient of friction is assumed to be a constant value of 0.02.

$$\text{Thrust Required} = (GW)(\mu_r) \quad (1)$$

McCollum (2017) noted that the available thrust for a C-17 is approximately 1,700 pounds per engine at ground idle, approximately 3,400 pounds per engine at high idle, and 10,000 pounds per engine at maximum continuous thrust (McCollum, 2017). To calculate fuel flow per hour, McCollum (2017) suggested multiplying thrust required per engine by the number of operational engines by the specific fuel consumption (SFC) for the respective thrust requirements. The specific fuel consumption values for the aforementioned power settings during taxi operations are 0.58, 0.41, and 0.33, respectively (McCollum, 2017).

$$\text{Fuel Flow} = (\text{Thrust Required})(\text{Number of Engines})(\text{SFC}) \quad (2)$$

Given an aircraft with a gross weight of 340,000 pounds, equation (1) can be used to determine that it will take 6,800 pounds of thrust for pilots to execute the taxi

maneuver. Dividing this value by four operational engines, it is determined that it will take 1,700 pounds of thrust per engine to generate the required force to execute the maneuver. Inputting these values into equation (2), the determined expected fuel flow to taxi the aircraft with four engines is outputted as 3,944 pounds of fuel per hour.

Accomplishing the same example using the reduced-engine taxi procedure (i.e., two engines operational), equation (1) reveals that it will take 3,400 pounds per engine to generate the required force to execute the taxi maneuver. Inputting these values into equation (2), the determined expected fuel flow to taxi the aircraft with two engines is outputted as 2,788 pounds of fuel per hour. McCollum (2017) proves using theoretical data that employing the reduced-engine taxi procedure nets a savings of approximately 1,156 pounds of fuel per hour of taxi.

The results of this rationalization model demonstrate that engines operating at higher thrust settings during surface operations operate more efficiently than engines operating at lower thrust settings. Therefore, it is better to use two engines than four engines to generate the required total thrust to execute the taxi maneuver. An engine's inherent efficiency characteristics demonstrate the innate benefits of employing the reduced-engine taxi procedure.

Data Analysis and Synthesis

This research presents two linear models and one simulation to assess the impacts of C-17 reduced-engine taxi procedures on USAF fuel consumption. The analyzed dataset included C-17 taxi characteristics and fuel consumption, engine-start malfunction trends, and the average annual number of C-17 sorties. The analysis and characterization

of this data provided a comparison of reduced-engine taxi procedures to current four-engine taxi practices. The parameters for these models were calculated using measures of central tendency, linear least-squares regression, and a Monte Carlo simulation.

Fuel-Savings Comparison Model

The fuel-savings comparison model estimated the average fuel flow per operational engine using a linear least-squares regression model based on seven variables. The original model used to predict average fuel flow per operational engine was:

$$f = \beta_1 t + \beta_2 T_{OAT} + \beta_3 d + \beta_4 r + \beta_5 W + \beta_6 Eng + \beta_7 (PHIK) + \beta_8 (KSUU) + \beta_9 (KCHS) + \beta_{10} (ETAR) + \beta_{11} \quad (3)$$

where f is the average fuel consumed per operational engine, t is the total taxi time in seconds, T_{OAT} is average outside air temperature in degrees Celsius, d is the total taxi distance in miles, r is the average taxi groundspeed in knots, W is the average aircraft gross weight in pounds during the taxi maneuver, Eng is the number of inoperative engines during the taxi maneuver, $PHIK$ is a binary variable defining an aircraft's taxi location as Joint Base Pearl Harbor-Hickam, $KSUU$ is a binary variable defining an aircraft's taxi location as Travis Air Force Base, $KCHS$ is a binary variable defining an aircraft's taxi location as Charleston Air Force Base, $ETAR$ is a binary variable defining an aircraft's taxi location as Ramstein Air Base, and $\beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6, \beta_7, \beta_8, \beta_9, \beta_{10}$, and β_{11} are estimated parameters resulting from the least-squares regression calculation. Table 1 presents the model's initial parameter estimations with an r-squared value of 0.9942.

Table 1. Model Outputs for Parameter Estimates of Average Engine Fuel Flow per Operational Engine

<i>Parameter</i>	<i>Coefficient</i>	<i>P-value</i>
Time (β_1)	0.2315	0.2521
Temperature (β_2)	-1.4114	0.6658
Distance (β_3)	-24.1338	0.7528
Groundspeed (β_4)	17.1323	0.05035
Weight (β_5)	0.001754	4.4764E-08
Engines Inoperative (β_6)	115.7287	0.03672
PHIK (β_7)	132.9770	0.1033
KSUU (β_8)	112.9459	0.2714
KCHS (β_9)	177.3779	0.05784
ETAR (β_{10})	92.6686	0.36579
Intercept (β_{11})	0	N/A

Variables with p-values greater than 0.051 were discarded as statistically insignificant to the model; an alpha value of 0.051 was selected as it produced a simple model with a strong goodness-of-fit statistic. The resulting fuel flow model was simplified to:

$$f = \beta_4 r + \beta_5 W + \beta_6 Eng \quad (4)$$

This model suggests aircraft groundspeed, aircraft gross weight, and the number of inoperative engines during the taxi maneuver are statistically significant predictors of the required average engine fuel flow per operational engine to execute the taxi maneuver.

Table 2 presents the results from the model's updated parameter estimations. The r-squared value for the resultant model is 0.9913.

Table 2. Refined Model Outputs for Parameter Estimates of Average Engine Fuel Flow per Operational Engine

<i>Parameter</i>	<i>Coefficient</i>	<i>P-value</i>
Weight (β_4)	0.002088	4.8264E-18
Engines Inoperative (β_5)	130.2207	0.01304
Groundspeed (β_6)	18.5329	0.0006145

To validate the fuel-savings model, the real-world data was compared to the model's approximated results. The model's average fuel flow per operational engine was calculated by inputting the actual average aircraft groundspeed, average aircraft gross weight, and number of inoperative engines from the actual data into the model's simplified equation. The standard error between the model and the actual results was determined by calculating the average of the absolute value of the difference between the approximated results to the actual four-engine data results and dividing by the actual results.

Because the MFOQA recorder does not generate data when less than three engines are operating on the aircraft, data for two-engine taxi scenarios could not be acquired. The fuel-savings comparison model was extrapolated to a two-engine scenario. The two-engine average fuel consumption per operational engine was calculated using actual data. The total average fuel flows per operational engine was multiplied by the total number of expected operational engines per the respective taxi methodologies to yield a total average fuel flow. The predicted two-engine total fuel flow results were compared to the actual four-engine average fuel flow data. The predicted two-engine total fuel flow approximations were subtracted from the actual average four-engine total fuel flow values and then averaged to find the mean of the total fuel flow differences for

each data sample. The outcome of this model was an initial estimation of the total fuel savings available per sortie in pounds of fuel consumed per hour.

Cost-Savings Simulation

The cost-savings simulation determined if the energy and fiscal savings of the reduced-engine taxi maneuver in the C-17 community are sufficient to compensate for the potential risks of engine-start malfunctions during the execution of the taxi maneuver. The fuel-savings comparison model was used to calculate the average fuel flows per operational engine for two sets of 52,000 data samples (the approximate total number of C-17 sorties flown in fiscal year 2016). One set of 52,000 simulations approximated the average fuel flow per operational engine assuming employment of reduced-engine taxi procedures on 50 percent of C-17 sorties and a two-percent operational risk factor. For sorties experiencing operational risk, the taxi parameters were doubled to account for the anticipated return to parking from the furthest possible point of taxi (i.e., runway entry). The second set of 52,000 simulations approximated the average fuel flows per operational engine assuming pilots utilized only four-engine taxi procedures.

To simulate hypothetical taxi patterns and calculate fuel consumption results for four-engine and reduced-engine taxi procedures, random values were created for each of the fuel-saving model's variables. These values were assumed between ranges of numbers based on realistic operational data from the actual data set. The aircraft gross weight was assumed between 315,000 and 585,000 pounds. The aircraft groundspeed was assumed between 5 and 20 knots. Although not a variable within the fuel-savings comparison model, the total taxi time was included to yield an estimate for the amount of

fuel saved in pounds. The total taxi time value was assumed between 30 and 1,000 seconds. The results of the random variable inputs were multiplied by the number of operational engines depending on the assumed taxi methodology to yield total average fuel flow.

To determine the total cost savings provided by employment of the reduced-engine taxi procedure, the total amount of fuel (in pounds) estimated by the 50-percent reduced-engine taxi data set with a two-percent operational risk factor was subtracted from the total amount of fuel (in pounds) estimated by the four-engine simulation set. This value was divided by 6.7 pounds per gallon and then multiplied by the current price point of aviation jet fuel per gallon (\$2.26 per gallon) according to data published by the Defense Logistics Agency (DLA, 2016). The results for 52,000 simulations (the estimated annual number of C-17 sorties) were calculated in increments of 2,000 simulations. The resulting figure was the fiscal savings produced by reduced-engine taxi procedures. The net cost and fuel savings accounted for the potential risks of engine-start malfunctions during the execution of the taxi maneuver according to the two-percent operational risk factor.

Optimal Taxi Policy Model

Finally, an optimal taxi policy was developed to prescribe either a four-engine or two-engine taxi strategy based on aircraft gross weight; symmetry is assumed to be important in maintaining control of the aircraft, so a three-engine reduced-taxi model was not considered. Per the results of the literature review, excessive jet blast was determined as the primary operational concern when considering a reduced-engine taxi methodology.

The results of the optimal taxi policy model will recommend guidelines for when pilots should employ the reduced-engine taxi procedure as influenced by engine pressure ratio (the total pressure ratio across a jet engine) and aircraft gross weight.

Two engines have the capability to generate sufficient thrust at higher thrust settings to effectively maneuver a C-17 operating at maximum gross weight. However, to mitigate risk caused by excessive jet blast, a maximum average value of 1.03 engine pressure ratio was selected as the optimized taxi-thrust setting. C-17 regulations stipulate that taxi operations must remain below 1.05 engine pressure ratio during taxi-in. If an engine exceeds 1.05 engine pressure ratio, then the engine must remain at an idle power setting for at least three minutes before engine shut-down to allow for sufficient engine cooling. Literature demonstrates that engines should have an appropriate warm-up period prior to nominal operations. As such, the maximum average value of 1.03 engine pressure ratio will serve as a guiding directive to maximize engine life and minimize engine overuse before it is sufficiently warmed.

The optimal taxi policy model will approximate the average engine pressure ratio via a linear least-squares regression analysis of seven dependent variables. The average engine pressure ratio was modeled as:

$$EPR = \alpha_1 t + \alpha_2 T_{OAT} + \alpha_3 d + \alpha_4 r + \alpha_5 W + \alpha_6 Eng + \alpha_7 (FF) + \alpha_8 \quad (5)$$

where EPR is the average engine pressure ratio, t is the total taxi time in seconds, T_{OAT} is average outside air temperature in degrees Celsius, d is the total taxi distance in miles, r is the average taxi groundspeed in knots, W is the average aircraft gross weight in pounds during the taxi maneuver, Eng is the number of inoperative engines utilized

during the taxi maneuver, FF is the average fuel flow per operational engine in pounds of fuel per hour, and α_1 , α_2 , α_3 , α_4 , α_5 , α_6 , α_7 , and α_8 are estimated parameters resulting from the least-squares regression calculation.

Table 3 presents the results from the model's initial parameter estimations. This table showcases the calculated coefficients and statistical significances of each respective value given the aggregate model. This model outputted an r-squared value of 0.811.

Table 3. Model Outputs for Parameter Estimates of Average Engine Pressure Ratio per Operational Engine

<i>Parameter</i>	<i>Coefficient</i>	<i>P-value</i>
Time (α_1)	4.9321E-06	0.02269
Temperature (α_2)	-1.3328E-05	0.5741
Distance (α_3)	-0.001387	0.05948
Groundspeed (α_4)	0.0002790	0.006737
Weight (α_5)	6.4567E-09	0.1082
Inoperative Engines (α_6)	0.001040	0.06168
Fuel Flow (α_7)	1.3072E-05	1.07672E-05
Intercept (α_8)	0.9870	3.2646E-53

Variables with p-values greater than 0.11 were discarded as statistically insignificant to the model. This p-value was intentionally selected to guarantee inclusion of average aircraft gross weight in the resulting optimal taxi model. This p-value indicated whether or not the variable had a statistical influence with the model. When the p-value is less than .11, the hypothesis that the coefficient is equal to zero is rejected. In other words, the coefficient is not zero and does influence the model with predicting the response variable.

The resulting average engine pressure ratio model was simplified to:

$$EPR = \alpha_1 t + \alpha_3 d + \alpha_4 r + \alpha_5 W + \alpha_6 Eng + \alpha_7 (FF) + \alpha_8 \quad (6)$$

Table 4 presents the results from the model's updated parameter estimations. The resulting model outputted an r-squared value of 0.809.

Table 4. Refined Model Outputs for Parameter Estimates of Average Engine Pressure Ratio

<i>Parameter</i>	<i>Coefficient</i>	<i>P-value</i>
Time (α_1)	4.87027E-06	0.022295835
Distance (α_3)	-0.001417351	0.050739197
Groundspeed (α_4)	0.000278939	0.006038265
Weight (α_5)	6.32138E-09	0.110169435
Engines (α_6)	0.001033512	0.059893841
Fuel Flow (α_7)	1.31132E-05	7.61212E-06
Intercept (α_8)	0.986734644	2.93914E-55

To validate the average engine pressure ratio model, the real-world data was compared to the model's approximated results. The model's average engine pressure ratio was calculated by inputting the actual average engine fuel flows, total taxi time, total taxi distance, aircraft ground speed, aircraft gross weight, and number of inoperative engines from the actual data into the model's simplified equation.

To determine the optimal taxi policy model, an experimental design was created employing the two derived models (the fuel-savings comparison model and the optimal taxi policy model). Because the optimal taxi policy prescribes either a four-engine or two-engine taxi strategy based on aircraft gross weight, the experiment was designed to output average engine pressure ratios per operational engine for aircraft gross weights starting at 285,000 pounds and terminating at 585,000 pounds in 10,000 pound increments. To model "worst-case" scenario, a value of 35 knots was assumed for the

average groundspeed during the taxi maneuver. C-17 regulations stipulate a maximum taxi speed of 40 knots.

The fuel-savings comparison model approximated average fuel flows per operational engine required to produce capable taxi thrust given incremental aircraft gross weights and a 35-knot average taxi groundspeed. The results of this model were incorporated as a variable in the optimal taxi policy model.

To determine the average engine pressure ratio per operational engine, the following parameters were assumed: 1.6 miles for the total taxi distance, 200 seconds for the total taxi time, incremental aircraft gross weights starting at 285,000 pounds and terminating at 585,000 pounds, and an average aircraft groundspeed of 35 knots. Given the assumed parameters, the simplified optimal taxi policy model approximated average engine pressure ratios for each incremental setting of aircraft gross weight. Two iterations of calculations were executed: one baseline iteration for the four-engine taxi methodology and a second iteration for the two-engine taxi methodology. These iterations allowed for a side-by-side comparison of each taxi methodology's thrust requirements given various aircraft gross weights.

Summary

This chapter outlined the methodology used to assess the impacts of C-17 reduced-engine taxi procedures on USAF fuel savings. Specifically, the experimental design developed two models (a fuel-savings comparison model and an optimal taxi policy model) and a cost-savings simulation. The results of the experimental design showcased a direct comparison of potential fuel savings between the two-engine and

four-engine taxi methodologies. The cost-savings simulation evaluated the monetary savings generated by reduced-engine taxi procedures assuming a 50-percent utilization rate and a two-percent operational risk factor. Finally, the optimal taxi policy model prescribed the use of either a four-engine or reduced-engine taxi methodology. The focus of this policy was to mitigate excessive jet blast risks and recommend ideal employment options to pilots based on aircraft gross weight.

IV. Analysis and Results

Chapter Overview

This chapter details the findings and results of the research questions. This research proposed the reduced-engine taxi methodology as a potential cost and energy-savings initiative. The results of the two models and simulation illustrate that the reduced-engine taxi procedure has the potential to yield significant fuel and cost savings for the USAF. The operational risk in terms of engine-start malfunctions is insignificant. Additionally, the analysis indicates that pilots have the ability to employ these procedures for maximum C-17 aircraft gross weights without producing excessive jet blast (as defined by engine pressure ratio).

Results of Fuel-Savings Comparison Model

In contrast to theoretical fuel-savings models, the MFOQA data analysis accounts for actual variances in pilot taxi behaviors (i.e., aggressive thrust utilization and excessive braking). The data produces comprehensive results and estimates for the global C-17 mission set given varying environmental conditions and aircraft operating configurations. Initial results indicate that C-17s can reduce fuel consumption and resource utilization by approximately 38.9 percent during the taxi phase per sortie if pilots perform reduced-engine taxi procedures in lieu of four-engine taxi procedures during surface operations before initial takeoff. Of note, the calculated average standard error between the actual data and the model's output was 8.1 percent for the four-engine data and 7.3 percent for the three-engine data. These standard errors illustrate an acceptable trend

between actual and predicted and lend towards acceptable confidence in the two-engine extrapolation.

Figure 1 offers a comparison between the average fuel flows required per operational engine for four-engine and two-engine taxi methodologies given various locations, environmental conditions, pilot behaviors, and aircraft configurations. The blue data points represent the actual four-engine fuel flow results per operational engine. The orange points represent the model's predictions for two-engine fuel flow results per operational engine given the actual aircraft groundspeed, gross weight, and number of inoperative engines. Figure 1 illustrates that the two-engine taxi methodology requires a higher fuel flow per operational engine to generate capable taxi thrust when compared to the four-engine taxi strategy.

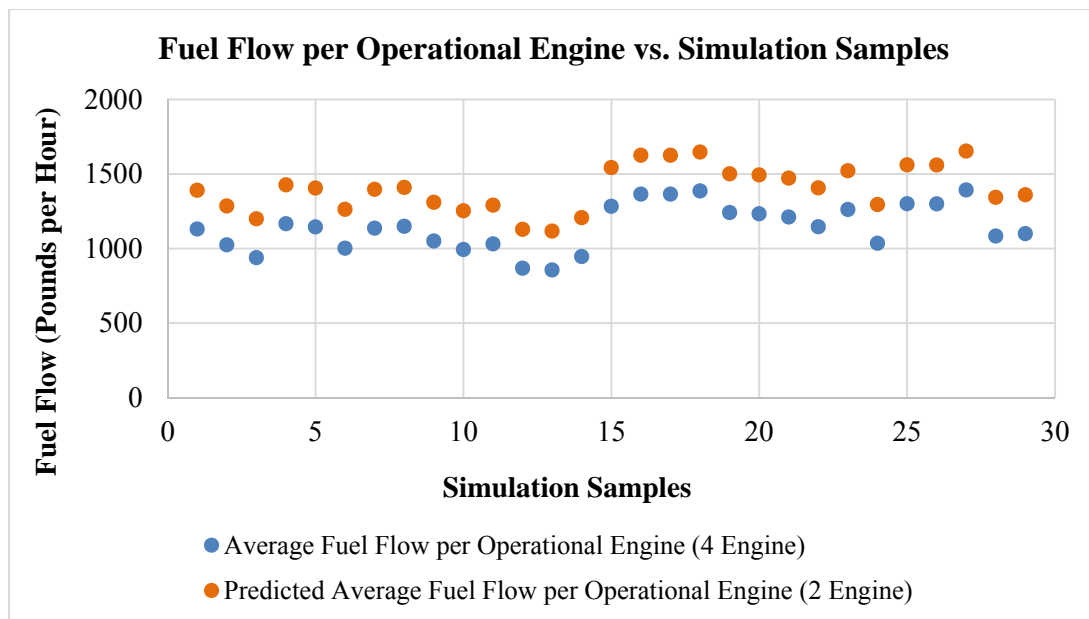


Figure 1. Four-Engine and Two-Engine (Predicted) Fuel Flow per Operational Engine Comparison

Figure 2 highlights the individual data point comparison between the actual four-engine total fuel flow results and the linear model's predictive two-engine total fuel flow results. Once again, the blue data points represent the actual four-engine total fuel flow results. The orange points represent the model's predictions for two-engine total fuel flow given the actual aircraft groundspeed, gross weight, and number of inoperative engines.

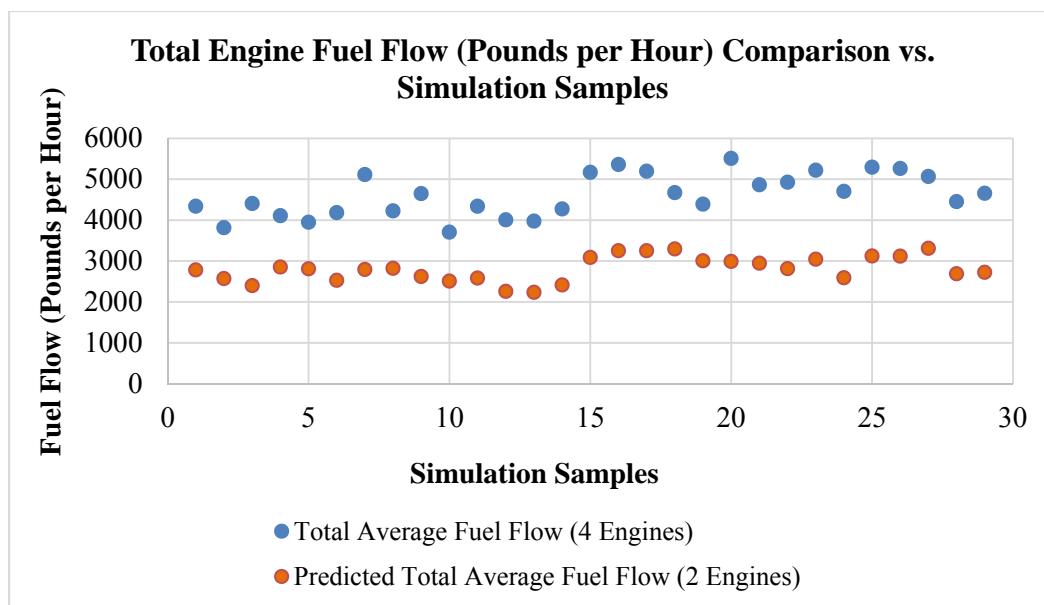


Figure 2. Four-Engine and Two-Engine (Predicted) Total Fuel Flow Comparison

Figure 2 depicts the trends of total average fuel burn for four-engine and two-engine taxi methodologies. This figure reveals that the reduced-engine taxi methodology consistently requires less total fuel consumption per hour than the four-engine taxi methodology. The comparison between figure 1 and figure 2 demonstrates that while greater fuel flow is required per individual engine in the

reduced-engine taxi methodology, less fuel flow is utilized across the aggregate number of engines when employing the proposed reduced-engine taxi strategy.

Table 5 depicts the comparative fuel and cost savings produced by reduced-engine taxi procedures in pounds of jet fuel per hour, gallons of jet fuel per hour, and cost per hour. The Defense Logistics Agency published price point of \$2.26 per gallon was utilized for the cost calculation (DLA, 2016). The data reveals that the MAF can save approximately \$609.41 per hour of C-17 surface maneuver by adopting the reduced-engine taxi methodology.

Table 5. Four-Engine versus Two-Engine Taxi Savings Comparison

	Fuel Flow (Pounds per Hour)	Fuel Flow (Gallons per Hour)	Cost Per Hour (\$ per Hour)
Four-Engine Taxi	4612.70	688.46	\$1,555.92
Two-Engine Taxi	2806.04	418.81	\$946.52
Difference	1806.65	269.65	\$609.41

Boeing's mathematical proof estimated a total fuel flow of 3,944 pounds per hour when employing a four-engine taxi methodology. Actual results from the analyzed data illustrate a total fuel flow average of 4,612.7 pounds per hour. These results demonstrate a discrepancy of 668.7 pounds per hour between the two methodologies. However, for the two-engine methodology, the mathematical model and Boeing's predicted fuel flow differ by only 18.4 pounds per hour (i.e., a predicted model estimate of 2,806.0 pounds per hour versus a Boeing estimate of 2,788 pounds per hour). Despite the preferred methodology, notable fuel and cost savings are observed through execution of a two-engine taxi strategy in lieu of a four-engine strategy.

Results of Cost-Savings Simulation

The Headquarters AMC Analyses, Assessments, and Lessons Learned Directorate (AMC/A9) reported that the MAF executed 52,195 C-17 sorties in fiscal year 2016. To estimate an approximation of the anticipated fuel and cost savings available via implementation of the reduced-engine taxi procedure, this number was rounded down to 52,000 sorties. Maintenance data indicates that C-17s experience only 18 documented engine-start malfunctions per year. Including deficiencies discovered during inspections and encountered during flight, the C-17 fleet documented 583 engine issues per one-year period. These values illustrate negligible operational risk considering the volume of sorties executed by C-17s per year (i.e., less than a 1.2 percent risk of engine malfunctions per year). Assuming “worst-case” scenario and considering potential risks presented by other system abnormalities, a two-percent operational risk factor was employed in the cost-savings simulation.

Table 6 illustrates the cost-savings simulation’s output of operational risks for 2,000 sorties to 52,000 sorties in increments of 2,000 sorties. Each row indicates the simulation’s expected outputs of operational risk penalties in terms of pounds of fuel, gallons of fuel, and cost in dollars per 2,000 sortie iteration. The aggregate of each column is annotated at the bottom of the table to demonstrate the predicted annual costs. If two percent of all sorties experience engine-start malfunctions and are required to return to parking from the furthest point of travel, then the operational risk penalty would equal approximately \$70,364 per year in fuel costs. Again, this is a high-side estimate.

Table 6. Operational Risk Penalties of Reduced-Engine Taxi Procedures

Number of C-17 Sorties	Operational Risk Penalty (Pounds of Fuel)	Operational Risk Penalty (Gallons of Fuel)	Operational Risk Penalty (Cost in \$)
2,000	7,719.93	1,152.23	\$2,604.04
4,000	9,367.24	1,398.10	\$3,159.70
6,000	7,874.21	1,175.25	\$2,656.08
8,000	8,767.74	1,308.62	\$2,957.48
10,000	7,955.25	1,187.35	\$2,683.41
12,000	10,068.47	1,502.76	\$3,396.23
14,000	9,413.56	1,405.01	\$3,175.32
16,000	6,807.90	1,016.10	\$2,296.39
18,000	6,892.74	1,028.77	\$2,325.01
20,000	8,142.55	1,215.31	\$2,746.59
22,000	7,788.25	1,162.42	\$2,627.08
24,000	8,173.39	1,219.91	\$2,756.99
26,000	8,329.09	1,243.15	\$2,809.51
28,000	9,102.14	1,358.53	\$3,070.27
30,000	7,275.58	1,085.91	\$2,454.15
32,000	9,456.23	1,411.38	\$3,189.71
34,000	8,625.84	1,287.44	\$2,909.61
36,000	6,660.70	994.13	\$2,246.74
38,000	5,662.38	845.13	\$1,910.00
40,000	6,561.68	979.36	\$2,213.34
42,000	6,387.67	953.38	\$2,154.65
44,000	7,388.41	1,102.75	\$2,492.21
46,000	9,227.47	1,377.24	\$3,112.55
48,000	8,101.26	1,209.14	\$2,732.66
50,000	9,054.26	1,351.38	\$3,054.12
52,000	7,796.61	1,163.67	\$2,629.90
TOTAL	208,600.53	31,134.41	\$70,363.76

Table 7 displays the potential cost savings for 2,000 sorties to 52,000 sorties in increments of 2,000 sorties. The fuel data for each row showcases the simulation's output per 2,000-sortie increment. The cost column demonstrates the cumulative benefit of cost savings in terms of dollars via employment of the two-engine taxi methodology.

The cumulative fuel savings in terms of pounds of fuel and gallons of fuel are found by summing the data in the respective columns. Assuming a \$2.26 price point per gallon of fuel (DLA, 2016), the simulation reveals that reduced-engine taxi procedures have the capacity to save approximately 1,178,590 gallons of fuel per year (i.e., \$2,663,613 in annual fuel costs). These savings include a deduction for the aforementioned costs due to operational risk.

Table 7. Total Fuel and Cost Savings Produced by Comparison of Four-Engine and Reduced-Engine Taxi Procedures per Number of C-17 Sorties

Number of C-17 Sorties	4-Engine Fuel Expended (Pounds of Fuel)	2-Engine Fuel Expended (Pounds of Fuel)	Fuel Savings (Pounds of Fuel)	Fuel Savings (Gallons of Fuel)	Cumulative Savings (Cost in \$)
2,000	1,614,548.17	1,256,042.87	358,505.30	53,508.25	\$120,928.65
4,000	1,557,461.80	1,268,922.87	288,538.93	43,065.51	\$218,256.71
6,000	1,554,937.20	1,253,132.65	301,804.55	45,045.45	\$320,059.44
8,000	1,559,324.15	1,242,861.60	316,462.55	47,233.22	\$426,806.51
10,000	1,574,816.32	1,240,974.17	333,842.16	49,827.19	\$539,415.95
12,000	1,549,721.11	1,245,690.47	304,030.64	45,377.71	\$641,969.57
14,000	1,570,244.75	1,264,410.60	305,834.15	45,646.89	\$745,131.54
16,000	1,569,904.01	1,217,647.95	352,256.06	52,575.53	\$863,952.24
18,000	1,542,938.15	1,260,076.56	282,861.59	42,218.15	\$959,365.25
20,000	1,578,042.84	1,261,638.44	316,404.40	47,224.54	\$1,066,092.71
22,000	1,576,386.74	1,249,956.52	326,430.22	48,720.93	\$1,176,202.00
24,000	1,564,752.14	1,274,722.89	290,029.25	43,287.95	\$1,274,032.77
26,000	1,540,042.51	1,287,326.80	252,715.71	37,718.76	\$1,359,277.17
28,000	1,543,129.76	1,225,032.18	318,097.58	47,477.25	\$1,466,575.76
30,000	1,562,161.62	1,232,695.60	329,466.01	49,174.03	\$1,577,709.07
32,000	1,552,290.90	1,277,416.94	274,873.96	41,025.96	\$1,670,427.75
34,000	1,542,807.51	1,256,422.56	286,384.95	42,744.02	\$1,767,029.24
36,000	1,531,867.23	1,262,955.35	268,911.88	40,136.10	\$1,857,736.83
38,000	1,551,590.28	1,253,222.23	298,368.05	44,532.54	\$1,958,380.38
40,000	1,613,153.73	1,261,389.09	351,764.64	52,502.19	\$2,077,035.32
42,000	1,538,320.24	1,264,626.25	273,693.99	40,849.85	\$2,169,355.98
44,000	1,587,064.26	1,275,085.28	311,978.99	46,564.03	\$2,274,590.68
46,000	1,530,675.17	1,266,077.10	264,598.07	39,492.25	\$2,363,843.16
48,000	1,528,502.58	1,248,960.55	279,542.04	41,722.69	\$2,458,136.45

50,000	1,562,855.06	1,241,878.07	320,976.99	47,907.01	\$2,566,406.30
52,000	1,550,302.97	1,262,124.84	288,178.12	43,011.66	\$2,663,612.65
TOTAL	40,547,841.21	32,651,290.43	7,896,550.77	1,178,589.67	

Figure 3 demonstrates the cumulative savings available via employment of the reduced-engine taxi procedure versus number of C-17 sorties. The demonstrated relationship between C-17 sorties and cumulative savings in dollars exhibits linear behavior. With an r-squared value of 0.9993, the model (given the inputted assumptions) predicts that on average the MAF can save approximately \$51.82 in ground fuel consumption costs per C-17 sortie. This value illustrates a net savings despite a 50-percent utilization rate and a 2-percent operational risk penalty.

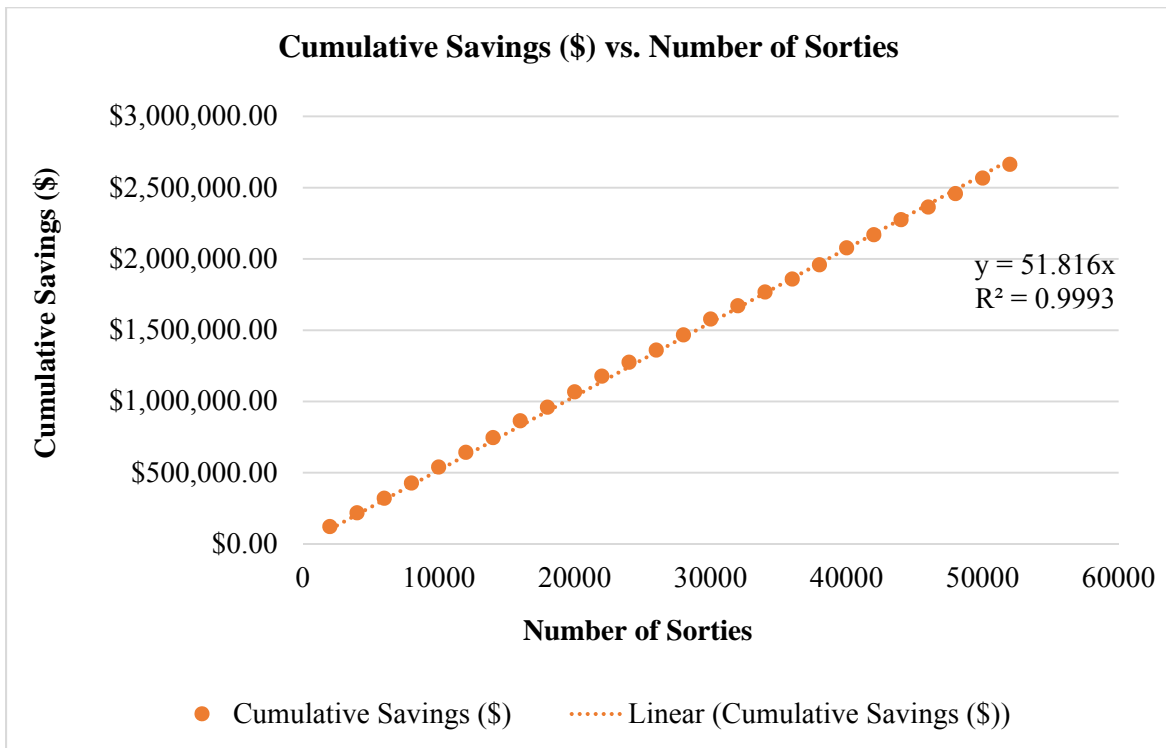


Figure 3. Cumulative Savings (\$) vs. Number of Sorties

To output higher fidelity savings values, the simulation can be edited to account for seasonal adjustments in aircraft gross weights and refined total taxi time data based on expected operating locations. Additional savings are available if pilots employ the reduced-engine taxi procedures on a more routine basis than the 50-percent employment prediction. Implementation of the reduced-taxi procedures have the ability to save millions of dollars for the DoD, the USAF, and AMC.

Results of Optimal Taxi Policy Model

The optimal taxi policy prescribes either a four-engine or two-engine taxi strategy based on aircraft gross weight and mitigation of risk caused by excessive jet blast (as defined by the aircraft's engine pressure ratio). The optimal taxi policy model averages variances in pilot taxi behaviors, environmental conditions, and aircraft configurations to create an approximated average engine pressure ratio per operational engine throughout the duration of the taxi maneuver. The results reveal that the two-engine taxi methodology has the capability to produce maneuverable taxi thrust for all aircraft gross weights (up to and including the maximum C-17 gross weight of 585,000 pounds) without exceeding the assigned average limit of 1.03 engine pressure ratio. Given identical parameters, the two-engine taxi technique requires an additional 0.0055 engine pressure ratio than the four-engine taxi maneuver.

The average standard error between the engine pressure ratio outputted by the optimal taxi policy model and the actual results was 7.2 percent. The average standard error between the model and the actual results for the actual three-engine taxi data was 8.8 percent. These standard errors illustrate an acceptable trend between actual and

predicted and lend towards acceptable confidence in the two-engine extrapolation.

Figure 4 illustrates the comparison between the optimal taxi policy model and actual engine pressure ratios per data sample.

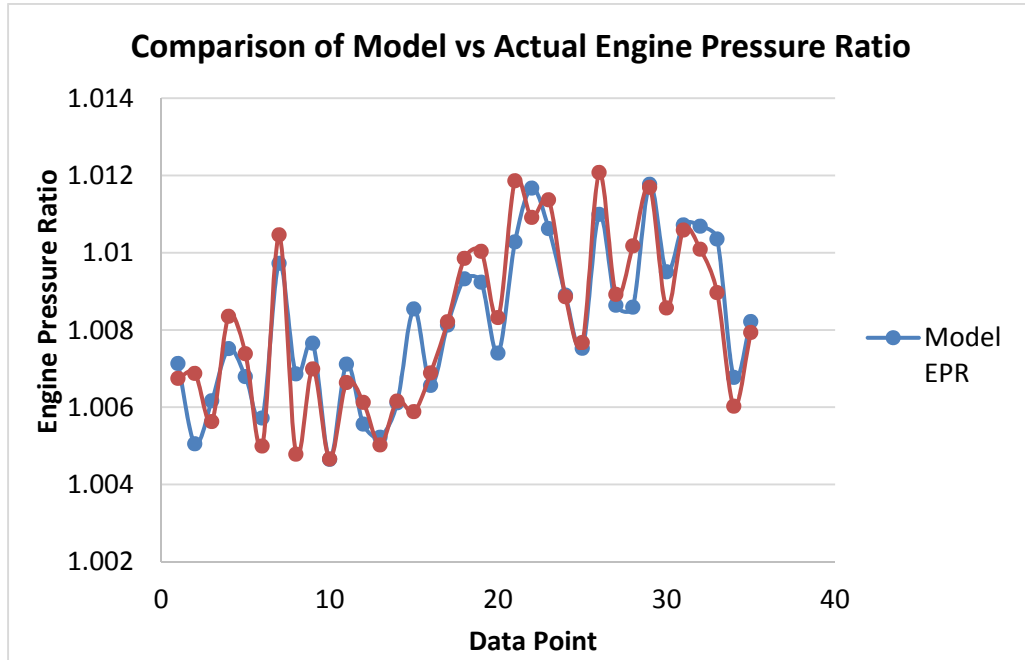


Figure 4. Comparison of Model vs. Actual Engine Pressure Ratios per Data Point

Figure 5 illustrates the average engine pressure ratio expected per operational engine according to aircraft gross weight when employing reduced-engine taxi procedures. The data demonstrates that the correlation between aircraft gross weight and average engine pressure ratio is linear. As aircraft gross weight increases, the thrust required to produce capable taxi thrust increases proportionately by a constant of $3.3703\text{E-}8$. This model yields a perfect r-squared value of 1.0 (i.e., a direct correlation).

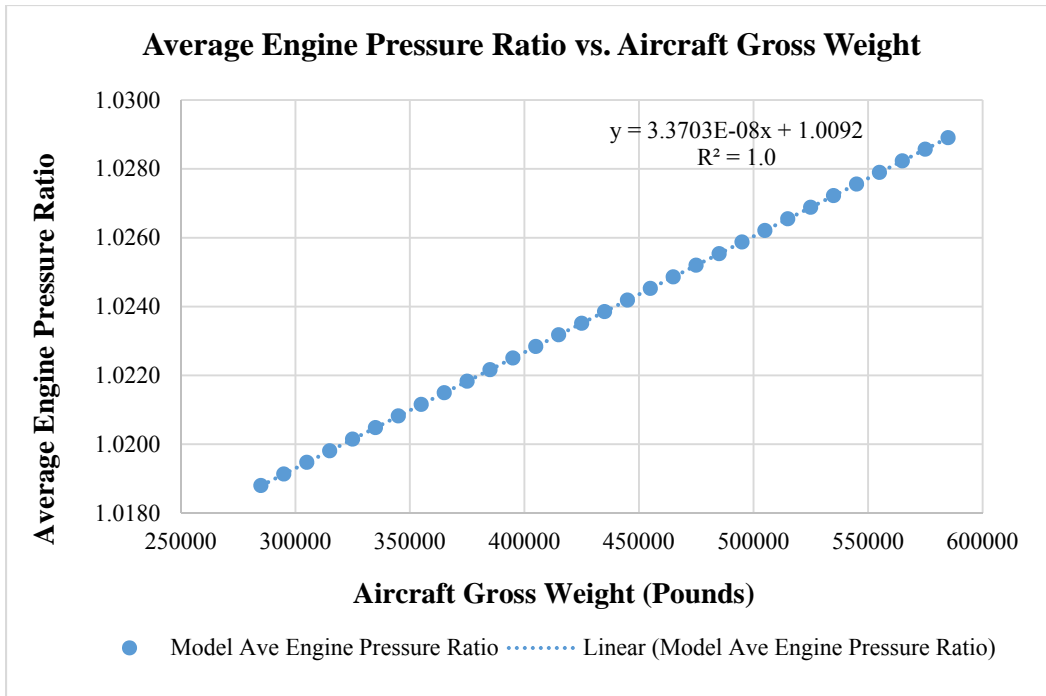


Figure 5. Average Engine Pressure Ratio vs. Aircraft Gross Weight

Table 8 displays the numerical data corresponding to the depicted results in Figure 5. Given a C-17 loaded to a maximum gross weight of 585,000 pounds, the average expected engine pressure ratio to produce capable taxi thrust was calculated as 1.0289. The experimental design illustrates that a lightweight C-17 (285,000 pounds) required an average engine pressure ratio per operational engine of 1.0188. These results establish that the average difference in engine pressure ratio to maneuver a lightweight C-17 and a maximum gross weight C-17 is approximately 0.0101 engine pressure ratio.

Table 8. Modeled Two-Engine Average Engine Pressure Ratio Requirements per Aircraft Gross Weight

Aircraft Gross Weight (Pounds)	Model Average Engine Pressure Ratio
285,000	1.0188
295,000	1.0191
305,000	1.0195
315,000	1.0198
325,000	1.0201
335,000	1.0205
345,000	1.0208
355,000	1.0212
365,000	1.0215
375,000	1.0218
385,000	1.0222
395,000	1.0225
405,000	1.0228
415,000	1.0232
425,000	1.0235
435,000	1.0239
445,000	1.0242
455,000	1.0245
465,000	1.0249
475,000	1.0252
485,000	1.0255
495,000	1.0259
505,000	1.0262
515,000	1.0265
525,000	1.0269
535,000	1.0272
545,000	1.0276
555,000	1.0279
565,000	1.0282
575,000	1.0286
585,000	1.0289

Temporary aircraft stops and delays along the route of taxi decrease the average engine pressure ratio since the engine remains at idle thrust for the duration of the delay.

The engine pressure ratio required for breakaway thrust from a stopped position is typically higher than the taxi average. Engines intended for taxi should have sufficient time to properly warm-up period prior to initiation of taxi while pilots complete their “before taxi” checklists. If additional engines are started during the route of taxi, a maximum engine pressure ratio limit may be necessary to minimize engine wear.

Of note, current regulations do not specify an engine pressure ratio limit for C-17 engines on initial taxi out. Analysis of the provided MFOQA data reveals that pilots currently utilize engine pressure ratios up to 1.129 on initial taxi out. Of the data samples analyzed, an average maximum of 1.06 engine pressure ratio was observed. Table 9 illustrates the maximum engine pressure ratio observed for each engine per taxi-out data sample.

Table 9. Maximum Engine Pressure Ratio Observed for Each Engine per Taxi-Out Data Samples

Data Point	EPR 1	EPR 2	EPR 3	EPR 4
1	1.0625	1.058594	1.070313	1.0625
2	1.046875	1.050781	1.050781	1.046875
3	1.046875	1.039063	1.039063	1.042969
4	1.058594	1.0625	1.058594	1.050781
5	1.0625	1.058594	1.066406	1.0625
6	1.113281	1.128906	1.117188	1.105469
7	1.070313	1.0625	1.054688	1.058594
8	1.0625	1.058594	1.058594	1.054688
9	1.070313	1.074219	1.078125	1.066406
10	1.046875	1.046875	1.039063	1.035156
11	1.066406	1.066406	1.074219	1.058594
12	1.054688	1.054688	1.0625	1.054688
13	1.027344	1.035156	1.035156	1.027344
14	1.046875	1.046875	1.054688	1.046875
15	1.054688	1.0625	1.0625	1.078125
16	1.089844	1.09375	1.097656	1.097656

Summary

Reduced-engine taxi procedures have the potential to yield significant savings for the USAF. The MAF can reduce fuel consumption and resource utilization by approximately 38.9 percent during the taxi phase per sortie if pilots perform reduced-engine taxi procedures in lieu of four-engine taxi procedures during surface operations before initial takeoff. The cost-savings simulation revealed that reduced-engine taxi procedures have the capacity to save 1,178,590 gallons of fuel per year (\$2,663,613 in annual fuel costs). Lastly, the two-engine taxi methodology has the capability to produce maneuverable taxi thrust for all aircraft gross weights (up to and including the maximum C-17 gross weight of 585,000 pounds) without exceeding the assigned average limit of 1.03 engine pressure ratio.

V. Conclusions and Recommendations

Chapter Overview

This chapter summarizes the research's major conclusions, outlines their significance, and offers recommendations for future action and study. The intent of this research was to explore the potential fuel savings and subsequent fiscal advantages gained by the C-17 community adopting a practice of taxiing on a reduced number of engines prior to initial takeoff. The research presented two linear-regression models and a simulation estimating the MAF's prospective fuel and cost savings resulting from implementation of the proposed taxi methodology. To increase the fidelity of the savings' approximations, operational risks due to engine-start malfunctions and subsequent back taxi maneuvers were considered, measured, and incorporated into the simulation. Lastly, the optimal taxi policy prescribes the use of either a four-engine or two-engine taxi strategy based on aircraft gross weight.

Conclusions of Research

This research determined that significant C-17 fuel and costs savings are available via the employment of reduced-engine taxi procedures. A total of three observations were discovered as a result of this study. First, on an annual basis, the MAF has the capacity to save approximately 1,178,590 gallons of jet fuel (i.e., \$2,663,613 in fuel costs). Second, if two percent of all sorties experience engine-start malfunctions and are required to return to parking from the furthest point of travel, then the operational risk would equal approximately \$70,364 per year in fuel costs. These costs were included as a deduction in the total savings referenced above. The resulting savings overwhelmingly

favor reduced-engine taxi procedures from a fiscal perspective. Third, the optimal taxi policy model showcases that the two-engine taxi methodology has the ability to produce capable taxi thrust for all aircraft gross weights (up to and including the maximum C-17 gross weight of 585,000 pounds) while remaining below an average engine pressure ratio of 1.03.

Literature acknowledges that reduced-engine taxi procedures can serve as an effective fuel-savings initiative with minimal risk to operations. Page (2009) documented that this taxiing strategy can “[reduce] ground fuel burn by up to 40 percent.” This research’s fuel-savings comparison model revealed the MAF can reduce fuel consumption and resource utilization by approximately 38.9 percent during the initial taxi phase per sortie. These conclusions substantiate literature and offer an opportunity for the MAF to minimize waste and save fuel and money.

The presented models and simulation illustrate that the MAF has the capacity to save approximately 1,178,589.67 gallons of jet fuel per year (i.e., \$2,663,612.65 in annual fuel costs). These savings are based on three assumptions: future operations remain commensurate with historical operational precedents (i.e., approximately 52,000 C-17 sorties per year), pilots will utilize the proposed two-engine taxi strategy on 50 percent of sorties, and engine-start malfunctions will occur on two percent of sorties. Table 7 outlines the approximated savings per number of C-17 sorties flown per year in increments of 2,000 sorties from 2,000 to 52,000 sorties.

Lastly, the optimal taxi policy model showcases that the two-engine taxi methodology has the ability to produce capable taxi thrust for all aircraft gross weights (up to and including the maximum C-17 gross weight of 585,000 pounds) without

exceeding the assigned average limit of 1.03 engine pressure ratio. These results demonstrate that on average jet blast will not be an issue during the course of a nominal aircraft taxi pattern. Given identical parameters, the two-engine taxi technique requires an additional 0.0055 engine pressure ratio than the four-engine taxi maneuver. The implementation of an absolute maximum engine pressure ratio limit requires further investigation during specific portions of the taxi phase. Depending on taxiway slope and aircraft gross weights, a maximum engine pressure ratio limit could impact a pilot's ability to effectively achieve required breakaway thrust and initiate movement for a C-17 along certain points on the route of travel without creating excessive jet blast. Analysis indicates that pilots are currently using engine pressure ratios up to 1.129 on initial taxi out with four engines.

Significance of Research

Reduced-engine taxi procedures are a tactical issue with operational and strategic-level impacts. In the execution of Rapid Global Mobility, the MAF's heavy reliance on energy makes it particularly vulnerable to minor shifts and adaptations in the energy market. The resource dependence theory highlights the need for USAF senior leaders to reduce fuel consumption within the confines of mission-driven risk management. Solutions that decrease an organization's dependence on resources will serve as a force multiplier and allow for greater operational flexibility and resilience in times of crisis. Reduced-engine taxi procedures offer an opportunity for the MAF to refine C-17 taxi procedures and directly improve fuel efficiency without adding significant risk to operations.

Overall, this research provides answers to the targeted research objectives and validates an opportunity for fuel and cost savings. The most beneficial discovery of this research was determining that the two-engine taxi methodology has the ability to generate capable taxi thrust for a maximum gross weight C-17. Literature acknowledges that the most significant concern when operating with a reduced-complement of engines is risk to the engines and airfield due to excessive jet blast. The results indicated that jet blast should not be of gross concern since two-engine taxi methodologies require only an additional 0.0055 engine pressure ratio than four-engine taxi methodology given identical parameters. Because the engine's efficiency-performance relationship is optimized at higher thrust settings, the taxi methodology produces observable and impactful fuel and cost savings.

This research provides data to substantiate reduced-engine taxiing procedures from a fiscal perspective. AMC should consider implementation of this taxi strategy and training aircrew to a new "reduced-engine taxi" checklist option prior to initial departure. This taxi strategy will fundamentally alter aircrew training and facilitate a culture shift in the delegation of aircraft duties during the taxi maneuver. In a global economy bound by limited resources, the USAF will gain a competitive advantage by efficiently leveraging its logistical resources.

Recommendations for Action

Literature emphasizes the innate benefits of reduced-engine taxi procedures throughout the commercial airline industry. AMC should consider the practical applications, risks, and opportunities associated with this procedure and afford pilots the

opportunity to exercise this practice as a valid taxi technique. This research recommends three immediate action items pertaining to implementation of the reduced-engine taxi maneuver: coordinate with Boeing to rework the C-17 consolidated checklist and flight manuals, install an incremental fleet-wide training and qualification program, and evaluate future aircraft recapitalization requirements intended to exploit and maximize savings during aircraft surface operations.

Adoption of the reduced-engine taxi procedure will require a substantial update to the C-17 flight manuals. In coordination with Boeing, AMC should tailor the current C-17 reduced-engine taxi procedures employed by Special Operational Low Level crews and make them applicable across the entire C-17 crew force. AMC should coordinate with Boeing to update the C-17 flight manuals and provide crews with comprehensive detail and education on the new process. Publication of a new consolidated checklist with inclusion of the “reduced-engine taxi” option will require reconfiguration of checklist steps and adaptations to new standards and norms.

Literature acknowledges that “crews who never use engine-out taxi procedures will consider them awkward while crews who consistently use them will consider them routine” (IATA, 2004). To educate and train crews to the new procedure, AMC and Air Education and Training Command should initiate an incremental fleet-wide training and qualification program. Instructors at the C-17 school house should be the first to receive this new qualification. Training an initial cadre will allow for standardization of instruction, robust development and evaluation of the new procedure, and more effective education during formalized training programs.

Lastly, from a macro perspective, AMC must evaluate the impacts of reduced-engine taxi procedures on future aircraft recapitalization requirements. As AMC begins to investigate the next-generation airlifter, the acquisition process should be tailored to consider margins for resource savings during various phases of flight. Electric taxi procedures may soon replace reduced-engine taxi strategies and serve as a future viable solution to streamlining costs, reducing harmful environmental emissions, and maximizing energy resources during airport surface operations. These steps will allow for substantive future savings and strengthen AMC's resilience in providing Rapid Global Mobility around the world.

Recommendations for Future Research

This research explored the viability of C-17 reduced-engine taxi procedures from a cost-savings perspective. This project did not consider any potential second and/or third order effects of reduced-engine taxi procedures. Future research could seek out and examine any such effects. The suggested research would generate a better understanding of potential limitations unique to USAF operations and allow for individualized tailoring of the strategy to match operational requirements and needs.

This research focused on the fuel and cost savings associated with C-17 reduced-engine taxi operations. AMC can implement this taxi strategy across the MAF community with airframe-dependent operational caveats that demand comprehensive investigation and research. For instance, air refueling platforms such as the KC-135 and KC-10 possess unique operational requirements that mandate engine starts at specific times prior to takeoff. Future analysis and exploration of these aircrafts' engine

capabilities is required to determine the feasibility of reduced-engine taxi employment in their respective communities.

Literature suggests that reduced-engine taxi procedures will become second-nature for pilots who practice the methodology. This research assumes young crew have the ability to effectively delegate duties and a single pilot can autonomously start an engine while the second crew members executes the taxi maneuver. Future analysis and experimentation can be conducted in a simulated environment to test and evaluate the capacity of crew members to safely perform this new procedure.

Summary

This chapter reviews this research's significant conclusions and contributions, recommendations for action, and recommendations for future research. Overall, this study demonstrates that reduced-engine taxi procedures have the potential to generate capable taxi thrust for C-17s regardless of aircraft gross weight. From a fiscal perspective, significant fuel and costs savings are available via optimized taxi procedures. These results indicate that current MAF taxi strategies have capacity to optimize resource utilization and explore efficiencies through the lens of the resource dependence theory. This research recommends that AMC evaluate the feasibility of reworking the C-17 consolidated checklist and flight manuals, installing an incremental fleet-wide training and qualification program, and evaluating future aircraft recapitalization requirements to cater towards employment of fuel savings during ground movements. Lastly, this research offers recommendations for future areas of investigation that can deepen the understanding and capability of fuel-savings initiatives in the USAF.

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Reduced-Engine Taxi: A Cost-Savings Exploration

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Introduction

Reduced-engine taxi procedures are a tactical issue with operational and strategic-level impacts. In the execution of Rapid Global Mobility, the MAF's reliance on energy makes it particularly vulnerable to shifts and adaptations in the energy market.

Because of the magnitude of costs associated with operating mobility aircraft in a fiscally-constrained environment, AMC must streamline its practices, optimize fuel usage, and decrease costs. The intent of this research was to explore the potential fuel savings and subsequent fiscal advantages gained by the C-17 community adopting a practice of taxiing on a reduced number of engines prior to initial takeoff. This research explored these procedures from a cost-savings and capability perspective.

Research Goals

This research will determine the answers to three research questions:

1. How much fuel can the MAF save by implementing reduced-engine taxi procedures?
2. How do potential fuel savings from reduced-engine taxi procedures compare to the risks of engine-start malfunctions and subsequent back taxi maneuvers?
3. How does aircraft gross weight impact the reduced-engine taxi procedure's average thrust requirements to produce capable taxi thrust during sustained periods of taxi?



Results

- The MAF has the capacity to save approximately 1.2M gallons of jet fuel per year (\$2.7M in fuel costs per year [assumes \$2.26 per gallon]) without adding significant risk to operations.
- Assuming a two-percent operational risk penalty, the cost of engine-start malfunctions and subsequent back taxi maneuvers would equal approximately \$70,364 per year in fuel costs.
- The two-engine taxi methodology has the ability to generate capable taxi thrust for a maximum gross weight C-17 without creation of excessive jet blast.

Number of C-17 Sorties	4 Engine Fuel Expended (Pounds of Fuel)	2-Engine Fuel Expended (Pounds of Fuel)	Fuel Savings (Pounds of Fuel)	Fuel Savings (Gallons of Fuel)	Operational Risk Penalty (Pounds of Fuel)	Operational Risk Penalty (Gallons of Fuel)	Operational Risk Penalty (Cost in \$)	Cumulative Savings (Cost in \$)
10,000	7,861,087.64	6,261,934.16	1,599,153.49	238,679.62	41,684.37	6,221.55	\$14,060.71	\$539,415.95
20,000	7,810,850.86	6,249,464.02	1,561,386.84	233,042.82	41,325.22	6,167.95	\$13,939.54	\$1,066,092.71
30,000	7,786,472.77	6,269,733.99	1,516,738.77	226,378.92	40,668.45	6,069.92	\$13,718.00	\$1,577,709.07
40,000	7,791,709.65	6,311,406.17	1,480,303.48	220,940.81	36,966.83	5,517.44	\$12,469.40	\$2,077,035.32
50,000	7,747,417.31	6,296,627.25	1,450,790.08	216,535.83	40,159.07	5,993.89	\$13,546.19	\$2,566,406.30
52,000	1,550,502.97	1,262,124.84	288,178.12	43,011.66	7,796.61	1,163.67	\$2,629.90	\$2,665,612.65
TOTAL	40,547,841.20	32,651,290.43	7,896,550.77	1,178,589.67	208,600.53	31,134.41	\$70,363.76	



Methodology

This research used a model and simulation typology to compare potential fuel and cost savings to the risks of engine-start malfunctions during reduced-engine taxi maneuvers.

This study modeled engine fuel flow based on the number of inoperative engines, aircraft gross weight, and average groundspeed during the taxi maneuver. Using this model, the research executed a simulation estimating expected annual savings. Finally, this study offered an optimal taxi policy model which prescribes either a two-engine or four-engine taxi strategy based on aircraft gross weight and minimization of excessive jet blast.

Implications

Results indicate that significant fuel and costs savings are available with negligible risk to operations via employment of C-17 reduced-engine taxi procedures.

Recommendations

1. Coordinate with Boeing to rework the C-17 consolidated checklist and flight manuals.
2. Install an incremental fleet-wide training and qualification program.
3. Evaluate future aircraft recapitalization requirements intended to exploit and maximize savings during aircraft surface operations.

Collaboration

HQ AMC/A9

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14. ABSTRACT Reduced-engine taxi procedures are a tactical issue with operational and strategic level impacts. In the execution of Rapid Global Mobility, the MAF's reliance on energy makes it particularly vulnerable to shifts and adaptations in the energy market. This dependence underpins the criticality of research exploiting margins for energy savings and optimization. This research explores the viability of C-17 reduced-engine taxi procedures from a cost-savings and capability perspective. This study models expected engine fuel flow based on number of operational engines, aircraft gross weight, and average aircraft groundspeed. Using this model, the research executes a cost-savings simulation estimating the expected annual savings produced by the proposed taxi methodology. Finally, this research proposes an optimal taxi policy model which prescribes either a two-engine or four-engine taxi methodology based on aircraft gross weight and minimization of excessive jet blast. The results indicate that significant fuel and costs savings are available via the employment of reduced-engine taxi procedures. On an annual basis, the MAF has the capacity to save approximately 1,178,590 gallons of jet fuel (\$2,663,613 in fuel costs) without adding significant risk to operations. The two engine taxi methodology has the ability to generate capable taxi thrust for a maximum gross weight C-17. This research recommends coordination with Boeing to rework checklists and flight manuals, installation of a fleet-wide training program, and evaluation of future aircraft recapitalization requirements intended to exploit and maximize savings during aircraft surface operations.					
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